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DESIGN AND PARAMETRIC SIZING OF DEEP SPACE HABITATS SUPPORTING NASA'S HUMAN SPACE FLIGHT ARCHITECTURE TEAM

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Abstract

NASA's Human Space Flight Architecture Team (HAT) is a multi-disciplinary, cross-agency study team that conducts strategic analysis of integrated development approaches for human and robotic space exploration architectures. During each analysis cycle, HAT iterates and refines the definition of design reference missions (DRMs), which inform the definition of a set of integrated capabilities required to explore multiple destinations. An important capability identified in this capability-driven approach is habitation, which is necessary for crewmembers to live and work effectively during long duration transits to and operations at exploration destinations beyond Low Earth Orbit (LEO). This capability is captured by an element referred to as the Deep Space Habitat (DSH), which provides all equipment and resources for the functions required to support crew safety, health, and work including: life support, food preparation, waste management, sleep quarters, and housekeeping.The purpose of this paper is to describe the design of the DSH capable of supporting crew during exploration missions. First, the paper describes the functionality required in a DSH to support the HAT defined exploration missions, the parameters affecting its design, and the assumptions used in the sizing of the habitat. Then, the process used for arriving at parametric sizing estimates to support additional HAT analyses is detailed. Finally, results from the HAT Cycle C DSH sizing are presented followed by a brief description of the remaining design trades and technological advancements necessary to enable the exploration habitation capability.

INTRODUCTION

In support of the NASA Human Spaceflight Architecture Team (HAT), certain capabilities have been identified as essential in any future mission planning beyond LEO, commonly referred to as "Deep Space". These capabilities form a "Capabilities Driven Framework" that is used to formulate approaches for human missions to cis-lunar space, the moon, Near Earth Asteroids (NEA), the moons and the Mars surface (referred to as Design Reference Missions (DRMs)). In order to carry out theses DRMS, Deep Space Habitation is a major required capability which is captured by a HAT element: the Deep Space Habitat (DSH). This paper will describe the process used to capture the functionality necessary for a DSH and the parameters and assumptions which both affect and guide the parametric sizing of a DSH.

The main tool used by the team is named EXAMINE (EXploration Architecture Model for IN-space and Earth-to-orbit). It is an architecture modeling framework developed at NASA LaRC and contains a collection of parametric performance and sizing tools and algorithms that enable users to model various types of architectural elements. Originating from a collection of existing NASA spacecraft sizing toolsets, it includes and expands upon JSC's Envision, MSFC's MER (Mass Estimating Relationships) database, and

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JSC's ALSSAT (Advanced Life Support Sizing Analysis Tool). EXAMINE provides detailed architecture element-specific sizing in mass, volume, and power for Levels 1, 2, and (occasionally) 3 detail. It also provides a framework for performing an integrated sizing analysis across all elements in an architecture concept, which enables trades and studies to improve DRM and element designs. The HAT DSH team provides inputs to an instantiation of the EXAMINE model to parametrically size a conceptual DSH element, which is then integrated into the sizing of all elements in a DRM. These inputs include mission parameters for a particular DRM, such as number of crew and mission duration and configuration inputs which drive the size and shape of a habitat concept. The sizing results from EXAMINE are formatted into what is referred to as a "Deep Space Habitat Baseball Card". This is a one page description, which includes parametric data from EXAMINE (mass and volume) and a notional picture. Figure 1 summarizes the process described.

DRM PARAMETERS

As described in the process chart, the first step in determining the functionality required is to make sure all the parameters which affect the sizing are accounted for. Even though the HAT considers numerous destinations and DRMs, there are certain parameters that affect the proper parametric sizing of a DSH. Consider these as inputs into the process, and are usually given by the team working the specific DRM. The major mission parameters which affect the parametric sizing include:

- Crew Size
- Mission Duration
- Accommodations for Science
- Crewed Operations during Specific Day/Night Cycles
- Operations in an Uncrewed Mode
- Radiation Protection for the Crew
- EVA Requirements and Interaction
- Redundancy Requirements
- Extendability (accommodations for any docking of other elements)
- Mobility Requirements
- Logistics & Consumables Strategy
- Power Supply (external or internal)
- Environmental Conditions in Transit or at Destination
- Lifetime Requirements
- Transportation Architecture Constraints
- Launch Vehicle Options and Payload Shroud Dimensions
- Lander Vehicle Options

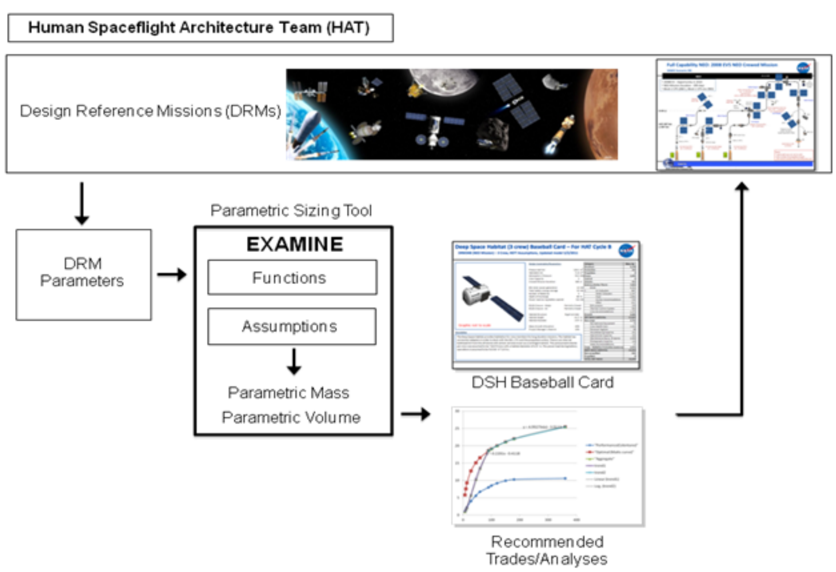

Figure 1: DSH Parametric Sizing Process in Support of HAT DRMs.

Functions and Assumptions

To parametrically size a DSH, the basic capability of providing a pressurized environment to support crew for long duration missions in deep space is broken into specific functions that are required regardless of destination or mission duration. Though most of these functions specifically address crew health and produc-

Table 1: Functions and Assumptions for HAT Cycle C

Function	Assumptions
Environmental Control & Life Support (ECLS)	• 20% mass for redundant components on critical ECLS subsystems • 30 days open loop contingency consumables for critical subsystems • Includes fire detection and suppression
Crew Accommodations	• Standard suite for 180-360 day deep space transfer (ref. Human Spaceflight Mission Analysis & Design) • Assumes larger freezer for missions longer than a year • Food, other crew items, sink(spigot), freezer, microwave oven, hand/mouth wash faucet, washer & dryer, 2 vacuums, laptop, trash compactor, printer, hand tools & accessories, test equipment, ergometer, photography equipment, exercise equipment, treadmill, table (microgravity)
Extra-Vehicular Activity (EVA)	• For contingent EVAs (DSH doesn't carry suits) • Assumed 35 m3 volume for contingency airlock (consistent with minimal airlock)
Thermal Control	• External fluid loop for heat acquisition using ammonia • Internal fluid loop for heat acquisition using 60% prop glycol/water • XX kW heat acquired from cabin & avionics rejected using ISS-type radiators w/ 10 mil Ag-Teflon coating (parametrically determined from power loading)
Avionics	• Provide Command, Control, and Data Handling (CC&DH), Guidance, Navigation and Control (GN&C) and Communications
Power	• 2 photovoltaic (3-junction GaAs) arrays each generating XX kW End-of-Life (EOL) power • EPCU 120 V dc PMAD (92% efficient) • 3 Li-ion batteries sized for 2 batteries generating XX kW for 1.2 hours
Protection	• 20 layers Multi-Layer Insulation (MLI) covering external habitat surface for passive thermal control • Cargo Radiation Protection • 5.8 cm water-wall covering crew quarters only (water included)
Maintenance and Spares	• Assume 1000 kg fixed and 500 kg each additional year with a 250 kg/m3 density
Habitat Structure & Mechanisms	• Metallic cylinder (4.27m diameter for Expendable Launch Vehicle (ELV) payload envelope dimensions) • Assumes 0.3 m for port extrusions, attachment structure, etc. • Secondary structure sized as 2.46 kg/m^2 of habitat structural area • Integration structure 2% of habitat gross mass • 4 x 0.5m^2 windows • 1 exterior hatch • 4 docking mechanisms • Atmospheric Pressure = 70.3 kPa (10.2 psi)
Reserves	• Margin growth Allocation - 20% of basic mass • Project Manager's Reserve - 10% of basic mass

tivity, some additional functions are included because the DSH is also a spacecraft. For each of the functions provided, a set of assumptions are carried within the EXAMINE tool to direct the sizing calculations. These assumptions are constantly being refined with subject matter experts. The necessary habitation functions and associated assumptions carried for the HAT Cycle C analysis are listed in Table 1.

HAT CYCLE C DSH DESCRIPTION

The Deep Space Habitat (DSH) provides a long duration habitation capability to support up to four crewmembers to live and work on long duration missions during travel to and operations at exploration destinations beyond LEO. The current DSH concept for the primary structure is envisioned to be a rigid aluminum-sandwich core hard-shell cylindrical pressure vessel. A secondary structure is sized at 2.46 kg/m^2 of habitat structural area, and an integration structure is sized at 2% of habitat gross mass. The DSH is operated at 70.3 kPa (10.2 psi) internal pressure to maintain commonality with the Multi-Purpose Crew Vehicle (MPCV). Three DSH concepts were sized for the Human Space Flight Architecture Team (HAT) Cycle 2011-C: 1) DSH only, 2) DSH plus one Space Exploration Vehicle (SEV), 3) DSH plus two SEVs. SEVs are mobile exploration vehicles enabling EVA and surface manipulation in NEA or surface missions. In all cases, the DSH pressurized volume assumed a notional four crew, 380 day mission, and in the two cases with habitable vehicles attached to the DSH (SEV and the MPCV), they are assumed to provide additional total available habitable volume for crew to utilize during the missions. The DSH has four windows, one exterior hatch and four passive International Docking System Standard (iDSS) based docking mechanisms: two mounted 180 degrees apart around the barrel of DSH and two located at the fore and aft endcaps of the DSH. An internal bulkhead and hatch located approximately 2 m (TBD) from the aft dome divides the total pressurized volume into two sections, each having docking ports leading to other attached habitable vehicles. These separable sections offer safe haven and EVA contingency capabilities in case of an emergency such as fire, debris impact or system failure, allowing the crew time to repair systems and potentially abort the mission. When attached to the DSH, the SEV and MPCV are assumed to provide increased total available volume for crew to inhabit during the missions. The DSH operational lifetime (both crewed and uncrewed) is at least 747 days to support orbital transit operations prior to crew arrival. All food and water required for a

Design Constraints/Parameters

Pressurized Vol.	152.4 m^3
Habitable Vol.	92.1 m^3
Atmospheric Pressure	70.3 kPa
Crew Capacity	4
Crewed Mission Duration	380 d
EOL Solar power generation	18 kW
Total battery energy storage	32 kW-h
Number of Batteries	3
Depth of Discharge	80 %
Power load during battery oper	13.1 kW
ECLSS Closure - Water	Partially Closed
ECLSS Closure - Air	Partially Closed
Habitat Structure	Rigid Cylinder
Habitat Length	11.08 m
Habitat Diameter	4.27 m
Mass Growth Allocation	20%
Project Manager's Reserve	10%

Description

The Deep Space Habitat provides habitation for crewmembers for long duration missions. The habitat has connection adapters in order to dock with the SEV, MPCV and the propulsion unit(s). There is an internal bulkhead 2m from the aft dome with airlock services to act as a contingent airlock. Includes assumption that 1 MPCV and no SEVs habitable volume can be utilized

Category	Mass, kg
Structure	**4,539**
Protection	**247**
Propulsion	**0**
Power	**1,286**
Control	**0**
Avionics	**453**
Environ./Active Therm	**8,026**
ECLSS	4,582
Air Subsytem	*1,028*
Water Subsytem	*1,969*
Food (storage)	*571*
Human Accommodations	*84*
Other	*930*
EVA systems	253
Thermal Control System	943
Crew Accommodations	2,249
Growth	**4,366**
DRY MASS SUBTOTAL	**18,917**
Non-cargo	**6,192**
Galley & Food System	2,281
Clothing	60
Miscellaneous Provisions	502
EVA	0
Recreational Equipment	100
Crew Health Care	250
Waste Collection and Personal Hygie	380
Housekeeping Supplies	252
Operational Supplies	191
Maintenance Equip. & Spares	2,021
Photography Supplies	120
Sleep Accommodations	36
Cargo - Radiation Protection (waterwall)	**2,055**
INERT MASS SUBTOTAL	**27,164**
Non-propellant	**763**
Propellant	**0**
TOTAL WET MASS	**27,927**

Figure 2: Notional DSH Overview (380 day crewed duration, no SEV concept).

Design Constraints/Parameters

Pressurized Vol.	143.7 m^3
Habitable Vol.	83.5 m^3
Atmospheric Pressure	70.3 kPa
Crew Capacity	4
Crewed Mission Duration	380 d
EOL Solar power generation	18 kW
Total battery energy storage	33 kW-h
Number of Batteries	3
Depth of Discharge	80 %
Power load during battery oper	13.6 kW
ECLSS Closure - Water	Partially Closed
ECLSS Closure - Air	Partially Closed
Habitat Structure	Rigid Cylinder
Habitat Length	10.48 m
Habitat Diameter	4.27 m
Mass Growth Allocation	20%
Project Manager's Reserve	10%

Description

The Deep Space Habitat provides habitation for crew members for long duration missions. The habitat has connection adapters in order to dock with the SEV, MPCV and the propulsion unit(s). There is an internal bulkhead 2m from the aft dome with airlock services to act as a contingent airlock .Includes assumption that MPCV and 1 SEV habitable volume can be utilized

Category	Mass, kg
Structure	**4,459**
Protection	**235**
Propulsion	**0**
Power	**1,295**
Control	**0**
Avionics	**453**
Environ./Active Therm	**8,041**
ECLSS	4,584
Air Subsytem	*1,028*
Water Subsytem	*1,970*
Food (storage)	*571*
Human Accommodations	*84*
Other	*931*
EVA systems	253
Thermal Control System	956
Crew Accommodations	2,249
Growth	**4,345**
DRY MASS SUBTOTAL	**18,828**
Non-cargo	**6,189**
Galley & Food System	2,281
Clothing	60
Miscellaneous Provisions	502
EVA	0
Recreational Equipment	100
Crew Health Care	250
Waste Collection and Personal Hygie	380
Housekeeping Supplies	252
Operational Supplies	188
Maintenance Equip. & Spares	2,021
Photography Supplies	120
Sleep Accommodations	36
Cargo - Radiation Protection (waterwall)	**2,055**
INERT MASS SUBTOTAL	**27,071**
Non-propellant	**765**
Propellant	**0**
TOTAL WET MASS	**27,837**

Figure 3: Notional DSH Overview (380 day crewed duration, one SEV concept).

mission are carried in the DSH.

The DSH ECLSS is an ISS heritage, partially closed air and water recovery system capable of providing 380 days of life support for four crew, plus 30 days of contingency. ECLSS systems are capable of autonomous operation, such as performing pressurized volume leak checks without crew interaction. The DSH provides ECLSS to the SEV and MPCV when they are docked, and can transfer consumables to each through the iDDS interface. The DSH is also assumed to include crew accommodations such as a sink, freezer, microwave oven, hand/mouth wash faucet, washer & dryer, two vacuums, laptop, trash compactor, printer, hand tools & accessories, test equipment, ergometer, photography equipment, exercise equipment, treadmill, and tables. Pressurized logistics and 1,500 kg of spares (for not only DSH but also SEV) are stowed in a TBD location within the habitat. While the main EVA function is performed from the SEV, stowage of EVA suits and spares within the DSH is TBD. If significant EVA is necessary for a mission, EVA suit maintenance will be performed in the DSH. An EVA may also be performed from the DSH in contingency scenarios, with at least one crew member remaining in the DSH at all times. The DSH also provides radiation protection from Solar Proton Events in the form of a five-centimeter thick water wall surrounding the crew quarters.

The DSH has two photovoltaic (3-junction GaAs) solar arrays for nominal DSH operations and keep alive operation of one SEV and one MPCV. An Electrical Power Control Unit (EPCU) distributes 28 Vdc Power Management and Distribution (PMAD) (92% efficient) throughout the DSH. Three Li-ion batteries provide power storage for use during ascent and periods of eclipse. The DSH is capable of sharing power, such as providing battery power to other elements during ascent or receiving surplus power from other elements when necessary. Passive thermal control is provided by 20 layers of MLI covering the DSH external surface. The DSH also provides radiators and an active heat exchanger system to maintain the thermal environment, using an external fluid loop for heat acquisition using ammonia and an internal fluid loop for heat acquisition using 60% prop glycol/water. ISS-type radiators with 10 mil Ag-Teflon coating are used to reject 6.5 kW of heat acquired from the cabin and avionics. The current DSH concept carries no Attitude Control System (ACS) or Reaction Control System (RCS), relying instead upon attached elements or a sled kit for attitude control and maneuvers. During crewed operations, the DSH is the primary provider of command, control, and communications of the integrated vehicle. The DSH

provides backup guidance, navigation, and position determination functions in the event of a failure of these systems on the primary propulsive element. Figures 2 and 3 represent the DSH concepts and design details.

TECHNOLOGY NEEDS

The HAT TechDev Team[1] methodology provides an architecture driven technology development assess-

Table 2: HAT Cycle DSH Technology Needs

OCT TA #	Title	Current TRL	x or D
2.4	Unsettled Cryo Propellant Transfer	3-4	x
2.4	In Space Cryogenic Liquid Acquisition	3-4	x
3.1	High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays	3	x
3.2	Regenerative Fuel Cell	2-3	x
3.2	Long Life Battery	3-4	x
4.3	Telerobotic control of robotic systems with time delay (w/ Demos)	3-5	x
4.5	Autonomous Vehicle Systems Management	3-5	D
4.5	Common Avionics	3	x
4.6	Automated/Auton. Rendez. & Docking, Prox Ops, Target Relative Nav	4-5	x
4.7, 6	Crew Autonomy beyond LEO	3-4	D
4.7	Robots Working Side-by-Side with Suited Crew (w/ Demos)	5-6	x
5.2	High Data Rate Forward Link (Flight) Communications	3	D
5.4	High Rate, Adaptive, Internet worked Proximity Communications	5	x
5.4	In-Space Timing and Navigation for Autonomy	4	x
5.5	Quad Function Hybrid Comm, Optical Ranging, RF Imaging System	3-4	x
6.1	Closed-Loop, High Reliability, Life Support Systems	3-5	x
6.1	Closed-Loop, High Reliability, Life Support Systems - ISS Demo	3-5	x
6.1	High Reliability Life Support Systems	3-5	D
6.1	High Reliability Life Support Systems - ISS Demo	3-5	D
6.2	Suit Port	4	x
6.3	Long Duration Spaceflight Medical Care	0-9	D
6.3	Long-Duration Spaceflight Behavioral Health	2-6	D
6.3	Microgravity Biomedical Counter-Measures for Long Duration Spaceflight	Various	D
6.3	Microgravity Biomedical Counter-Measures - Optimized Exercise Equipment	4-6	D
6.3, 6.1	Deep Space Mission Human Factors and Habitability	3-8	D
6.4, 11	In-Flight Environmental Monitoring	3	D
6.4	Fire Prevention, Detection & Suppression (reduced pressure)	3-5	D
6.4	Fire Prevention, Detection & Suppression - Large Scale Flight Demo	3-5	D
6.5	Space Radiation Protection Galactic Cosmic Rays (GCR)	Various	D
6.5	Space Radiation Protection Solar Particle Events (SPE)	Various	D
6.5	Space Radiation Shielding SPE	3	D
7.5, 4.7	Mission Control Automation beyond LEO	5-6	x
11.2	Advanced Software Development/Tools	3-4	x
12.1, 12.2	Inflatable: Structures & Materials for Inflatable Modules	3-5	x
12.1, 12.2	Lightweight Structures & Materials (In-Space Elements)	4-5	x
12.1, 12.2	Lightweight Structures & Materials (Manufacturing Techniques/Technologies)	4-5	x
12.3	Mechanisms for Long Duration, Deep Space Missions	3-4	x
14.1	In-Space Cryo Propellant Storage (ZBO LO2; Reduced/ZBO LH2)	3-4	x
14.1, 2.4	LO2/LH2 Cryo Flight Demo (CPST: Cryo Propellent & Storage Transfer)	3-4	x
14.2	Thermal Control	3-4	x

ment ("technology pull") of technology advancement needs across the spectrum of review cycle trade-studies associated with the flight elements (and destination DRMs). During HAT Cycle C the DSH team provided inputs based upon their assessment of technology needed for the required functionality assumed during the parametric sizing.

Initially, the HAT technology disciplines categories were created to help organize the various identified technologies into logical categorization groups. Subsequently, each TechDev entry was also cross-referenced to the Office of Chief Technology (OCT) Space Technology Roadmap Technology Area Breakdown Structure. Standardization of the OCT Breakdown Structure for discipline categorization is now the HAT Technology Development Assessment Team preferred standard. Table 2 shows a listing of technology needs identified by the HAT DSH team, with the associated OCT Technology Area (TA), current Technology Readiness Level (TRL), and indication of whether it is a Driver (D).

CONCLUSIONS

When considering a capabilities driven approach to exploration beyond LEO, the DSH team has utilized parametric tools, processes and results to help inform the HAT on a number of Design Reference Missions during 2011. The data and insight this provides is key in informing potential DSH design options and identifying enabling and enhancing technology needs. But its also reveals areas, that with a more detailed focus, might better define the functions necessary and the assumptions used within the EXAMINE parametric tool.

Future Trades include:

Galactic Cosmic Radiation (GCR) Protection - While the current parametric sizing takes into account a shielding requirement for Solar Proton Events (SPE), it does not currently provide for protection from GCR. This is an area being worked on many fronts, starting with the medical community. There are numerous options for providing protection from GCR within the DSH which include internal layout configurations offering optimal shielding mass for the crew. It could also include the addition of additional shielding mass to the structure of the DSH.

Launch Stack Packaging and In-space Integration - Because the DSH is a part of an integrated vehicle there are interfaces and dependencies that need to be further defined and studied. This includes looking at the launch configurations possible within assumed payload shroud restrictions for delivery to LEO. It should also consider the integration of the DSH into the In-space vehicle which includes propulsion and power generation elements.

Modular Approaches to Habitation[2] - Applying modularity in the design of the DSH structures and subsystems can spread the buildup of the overall habitation capability across several smaller elements. This allows for a more flexible habitation approach that accommodates various crew mission durations and levels of functionality in a capabilities driven approach. This would include the use of expandable structural approaches.

Incorporate Results of More Detailed Concept of Operations All Mission Phases[3, 4] - Develop more in-depth concept of operations for the DSH over the entire mission phases (particularly transit). This would help in identifying operations and resulting functions that could then be used to update the parametric functions and assumptions.

Incorporate Results of More Detailed Engineering Based Sizing[5] - Proper understanding of detailed subsystems that are part of the DSH is needed. This could be used to compare with the parametric analysis and validate mass, volume and power assumptions and results from the EXAMINE tool.

NOMENCLATURE

ALSSAT - Advanced Life Support Sizing Analysis Tool
DRM - Design Reference Mission
DSH - Deep Space Habitat
ECLS - Environmental Control and Life Support
EVA - Extra-Vehicular Activity
EXAMINE - Exploration Architecture Model for In-Space and Earth-to-Orbit
HAT - Human Space Flight Architecture Team
iDSS - International Docking System Standard
LEO - Low Earth Orbit
MER - Mass Estimating Relationships
MPCV - Multi-Purpose Crew Vehicle
NEA - Near Earth Asteroid
OCT - Office of Chief Technologist
SEV - Space Exploration Vehicle
TRL - Technology Readiness Leve

REFERENCES

[1] Scott D. Vangen, Carolyn R. Mercer, Julie A. Williams-Byrd, Jonette M. Stecklein, Leslie

Alexander, Shamim A. Rahman, Matthew E. Rosenthal, Diane S. Wiley, Stephan C. Davison, David J. Korsmeyer, Craig E. Kundrot, Eugene L. Tu, David H. Hornyak, and Tibor S. Balint. Critical Technology Determination for Future Human Space Flight. In *Global Space Exploration Conference*. GLEX-2012.09.3.3x12551, May 2012.

[2] M. Simon, D. Smitherman, and L. Toups. Potential Applications of Modularity to Enable a Deep Space Habitation Capability for Future Human Exploration Beyond Low-Earth Orbit. In *Global Space Exploration Conference*. GLEX-2012.05.3.6x12574, May 2012.

[3] S. J. Hoffman Ph.D. and L. Toups. Deep Space Habitat Concept of Operations for Extended Duration Transit Missions. In *Global Space Exploration Conference*. GLEX-2012.05.3.7x12291, May 2012.

[4] D.J. Neubek, A. Whitmire, and M. Simon. Factors Impacting Habitable Volume Requirements for Long Duration Missions. In *Global Space Exploration Conference*. GLEX-2012.05.3.4x12276, May 2012.

[5] M. Rucker and S. Thompson Ph.D. Developing a Habitat for Long Duration, Deep Space Missions. In *Global Space Exploration Conference*. GLEX-2012.05.3.8x12222, May 2012.